National Aeronautics and Space Administration

Intelligent (Autonomous) Power Controller Development for Human Deep Space Exploration

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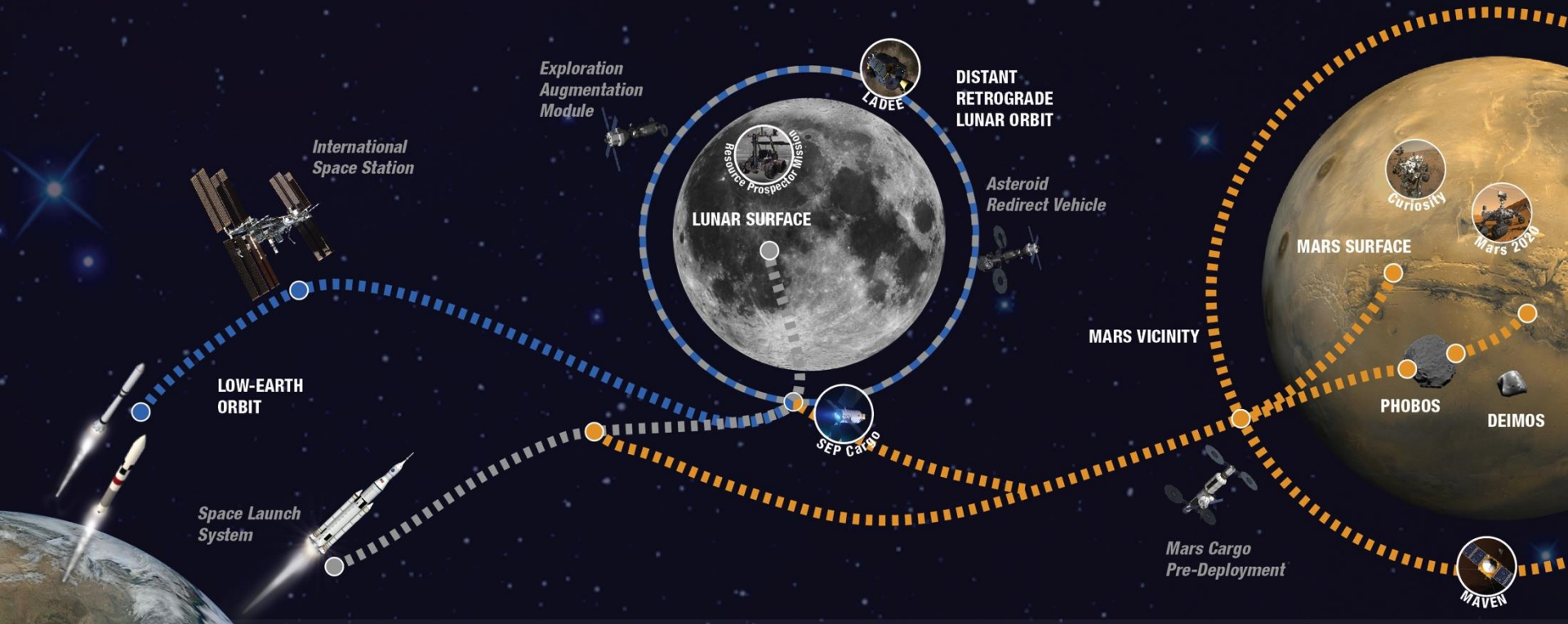
Discussion Topics

- Overview of NASA's Deep Space Exploration Vision
- Notional Deep Space Vehicle Power Architecture
- Autonomous Power Control Architecture
- Autonomous Power Control Functions
- Autonomous Controller Evaluation and Test
- Status and Future Plans
- Summary

EVOLVABLE MARS CAMPAIGN

A Pathways Approach to Exploration

EARTH DEPENDENT | **PROVING GROUND** | **EARTH INDEPENDENT**



THE TRADE SPACE

Across the Board | Solar Electric Propulsion • In-Situ Resource Utilization (ISRU) • Robotic Precursors • Human/Robotic Interactions • Partnership Coordination • Exploration and Science Activities

Cis-lunar Trades
- Deep-space testing and autonomous operations
- Extensibility to Mars
- Mars system staging/refurbishment point and trajectory analyses

Mars Vicinity Trades
- Split versus monolithic habitat
- Cargo pre-deployment
- Mars Phobos/Deimos activities
- Entry descent and landing concepts
- Transportation technologies/trajectory analyses

What is the Problem?

- Communication and recovery times are longer than any previous experience
- Communications bandwidth is a factor of 100 less than ISS

Mission	Communications bandwidth	Communications latency time
Deep Space Vehicle	< 2 Mbps (DSN)	15 to 45 minutes
Apollo / Orion	< 2 Mbps (DSN)	1- 2 seconds
ISS	300–800 Mbps (TDRS)	Real-time

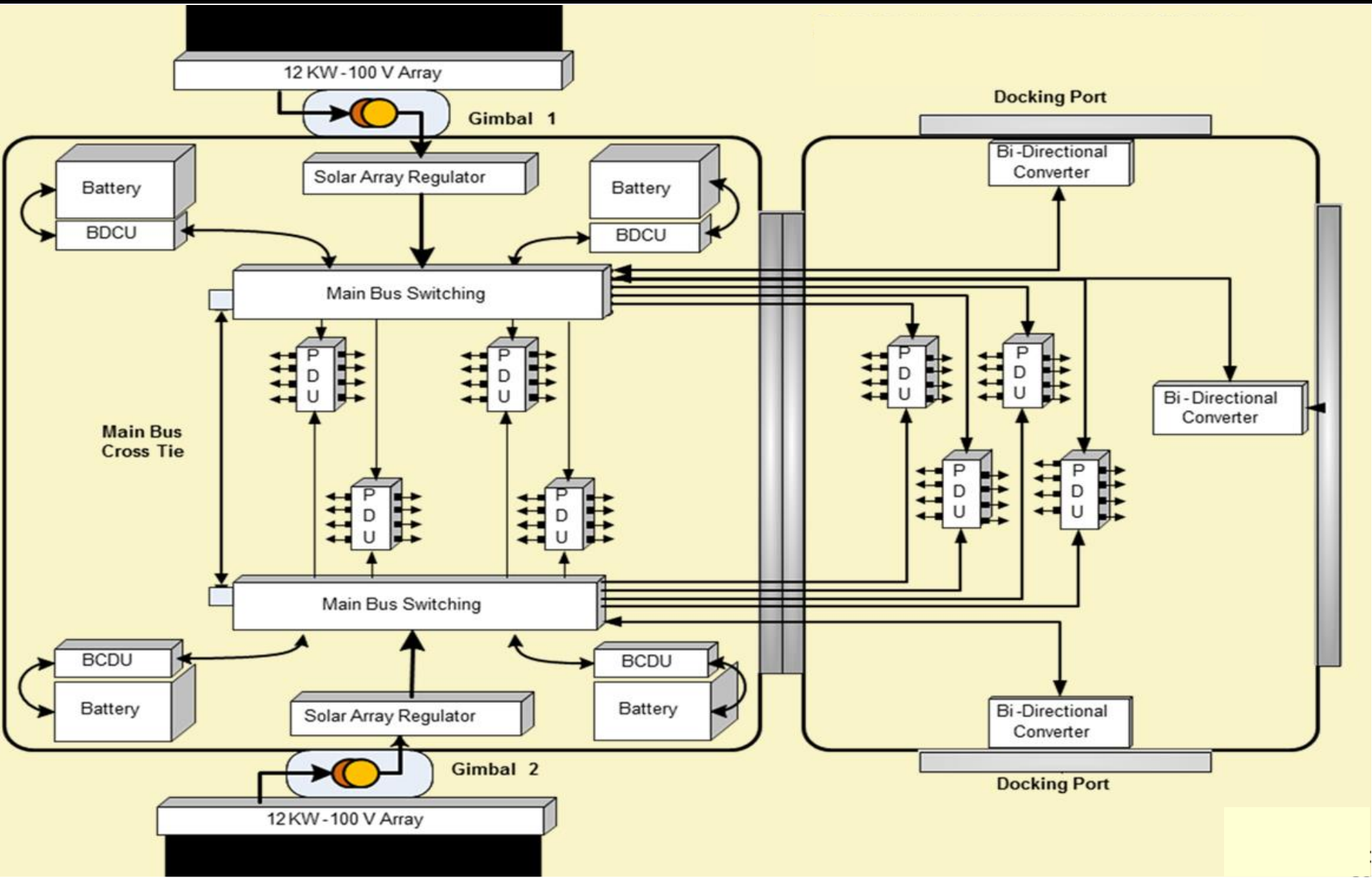
- Power Is Most Critical System On Board Vehicle
  - Every system on the vehicle needs power
  - Electric Power System (EPS) will need a high level of availability
  - Electric Power System (EPS) will need to operate autonomously for long periods of time

Notional Deep Space Vehicle
Electrical Power System Characteristics

- Multi-junction solar array power
  - 24 kW for user loads
  - 50 – 300+ kW for electric propulsion
- Two independent power channels with multi-level cross-strapping
- Lithium Ion battery storage
  - 300+ amp*hrs
  - Sized for 1.5 hr eclipses
- Distribution
  - 120 V secondary (SAE AS 5698 power quality Spec)
  - 2 kW power transfer between visiting vehicles

Notional Deep space vehicle concept

Notional Deep Space Vehicle Power Architecture



Autonomous Power Control Architecture

What is Autonomous Power Control?

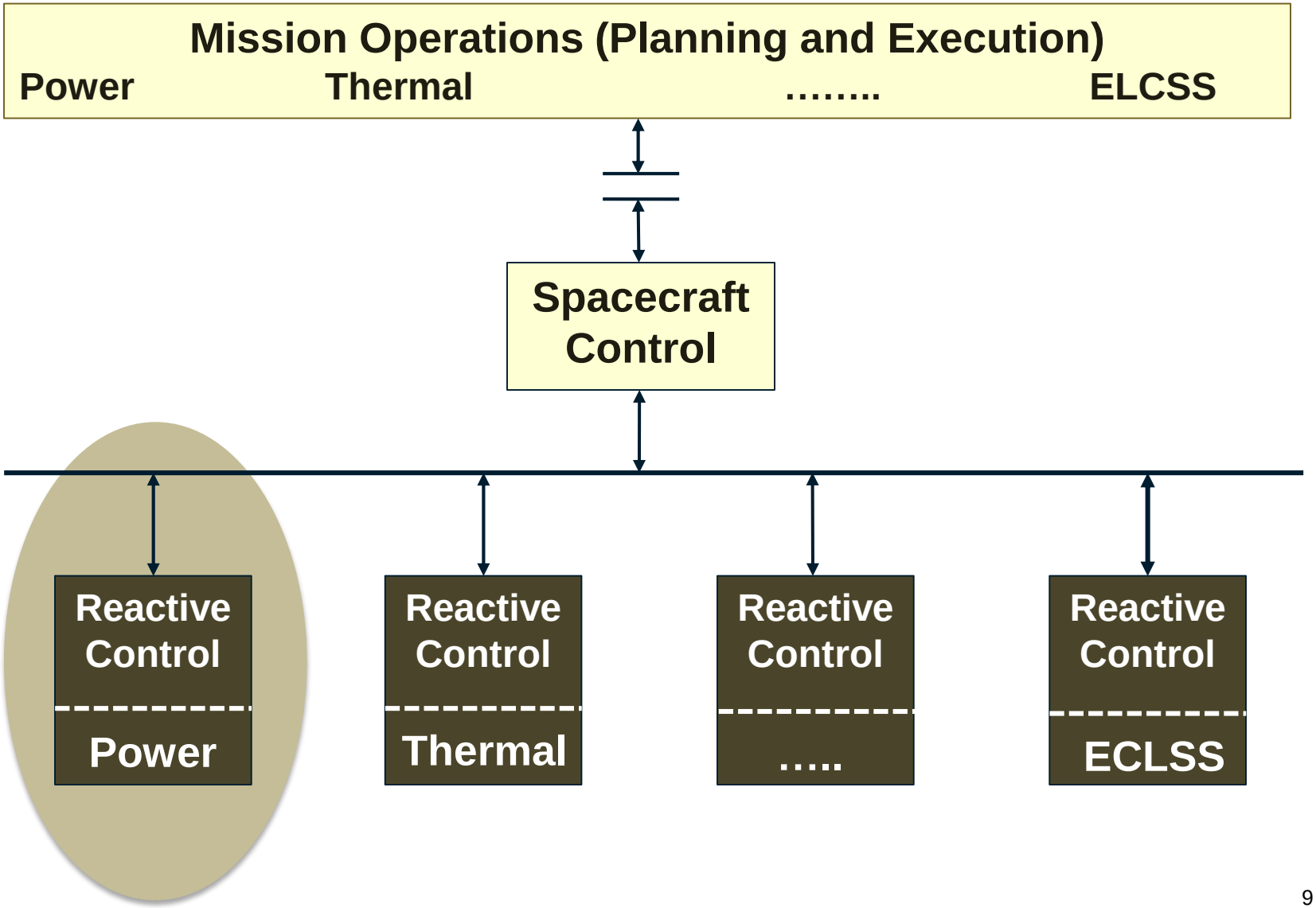
Exploration Systems

Near Earth Systems

An Intelligent Power Controller utilizes advanced hardware and control technology and works in conjunction with the ground mission operations and the vehicle manager to autonomously manage and control

- **Distributed power generation and storage assets**
- **Power distribution networks**
- **Loads**

Typical Spacecraft Control Architecture



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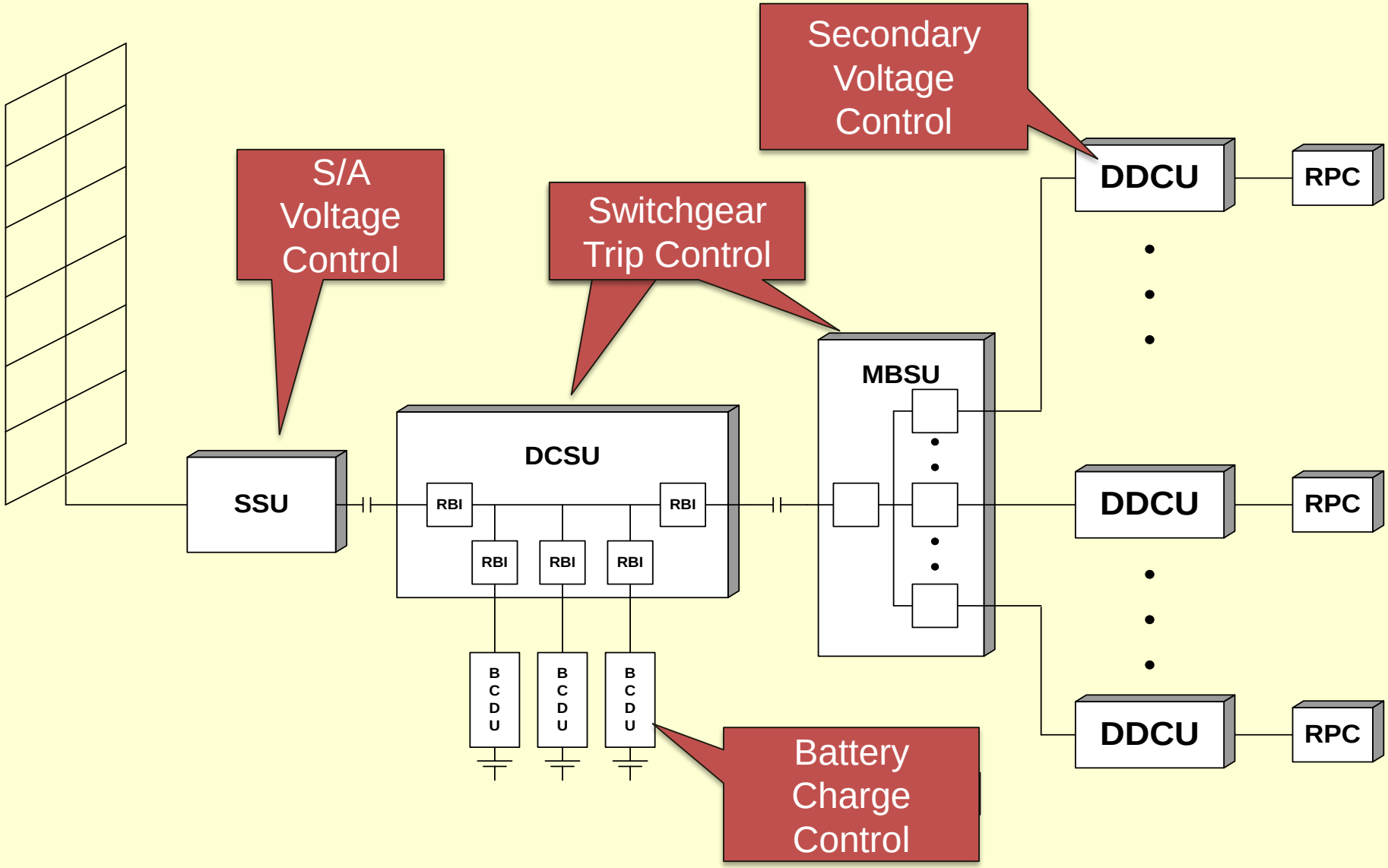
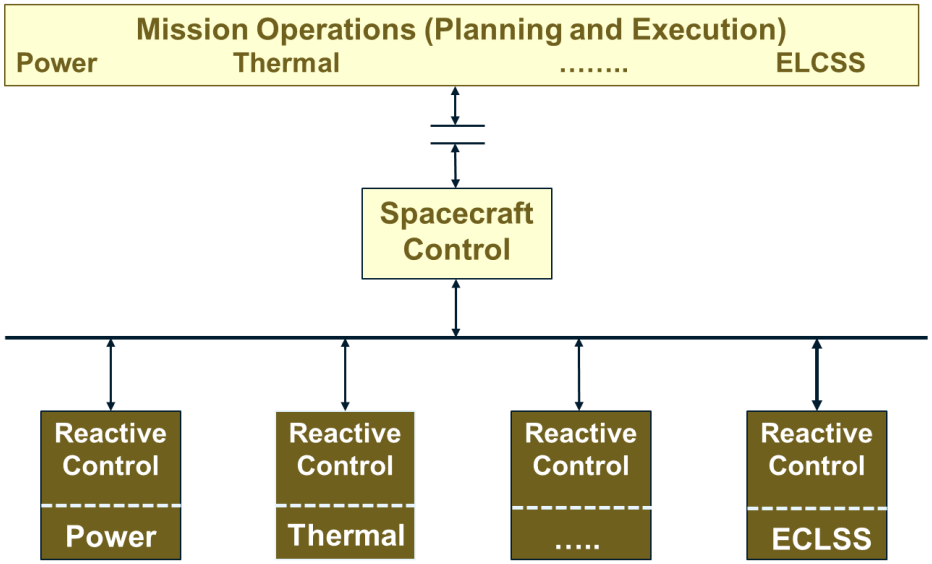
Power System Reactive Layer Controller

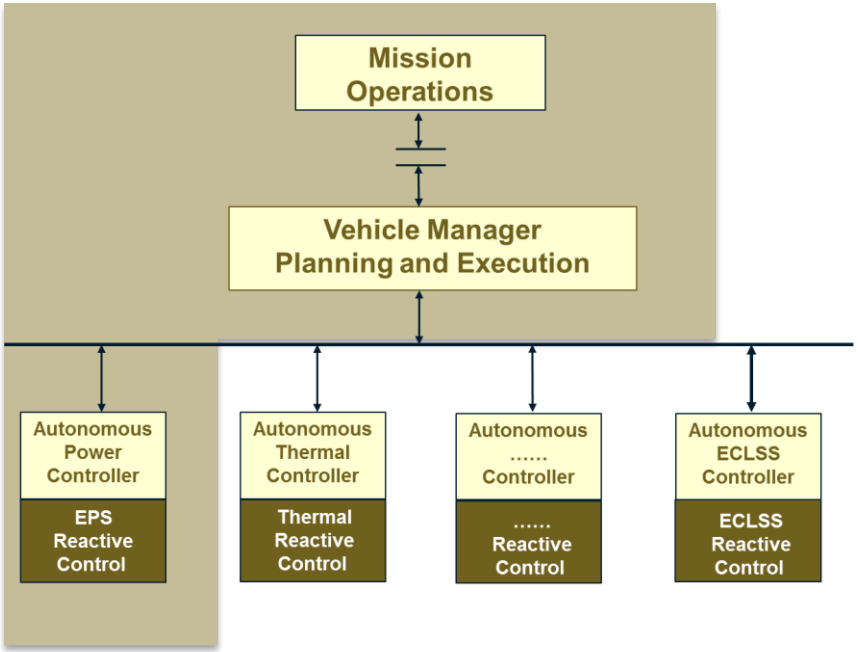


Traditional vs Autonomous Spacecraft Controller

Traditional Spacecraft Controller Architecture



Autonomous Spacecraft Controller Architecture



Transitioning some traditional ground based control functions to the vehicle

Development of an Autonomously Controlled Spacecraft is consistent with the "Future of Human Space Exploration" roadmap and enables the transition from "Earth Reliant" systems to "Earth Independent Systems"

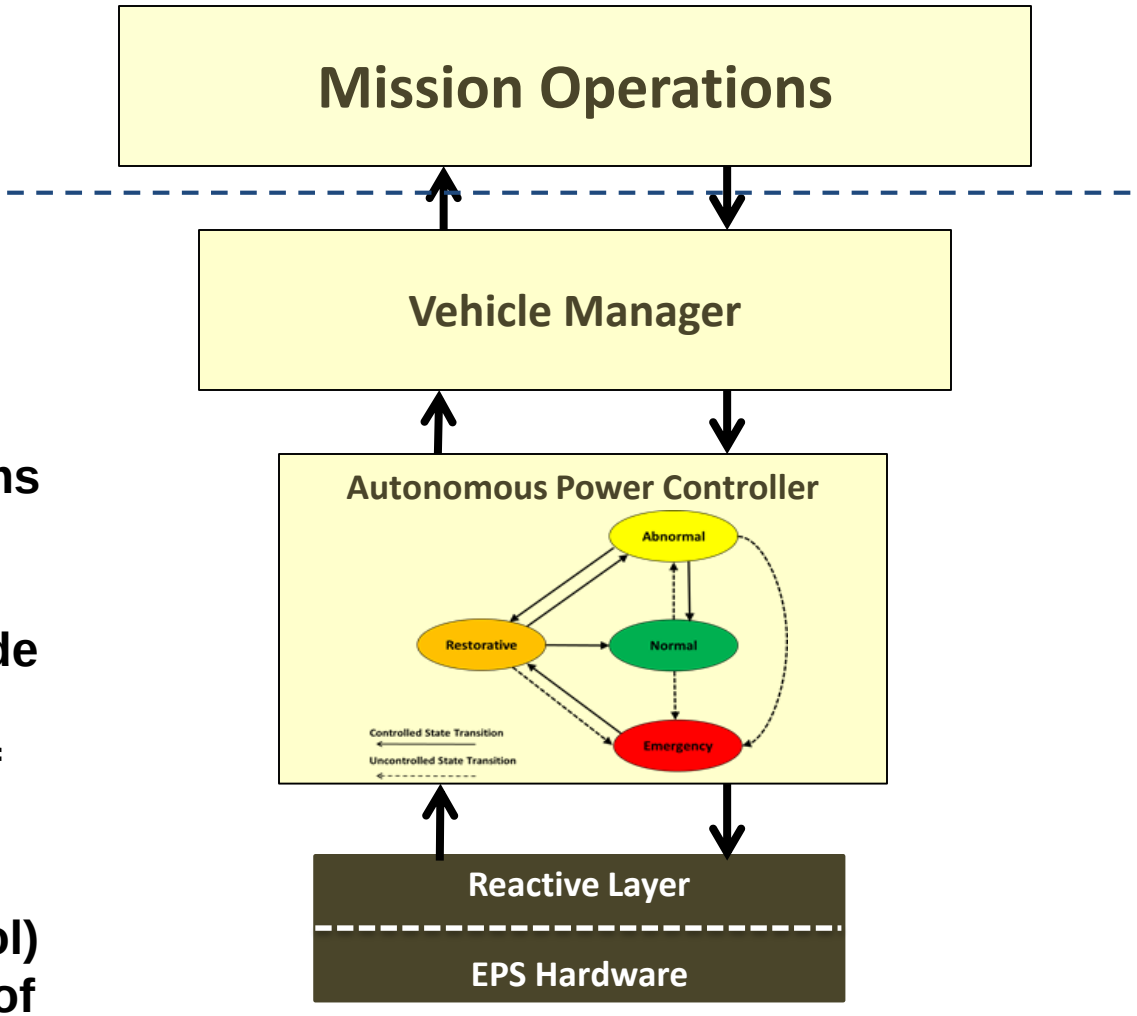
Simplified Autonomous Control Architecture

Mission Operations
- Monitors vehicle operations
- Adjusts long term mission objectives

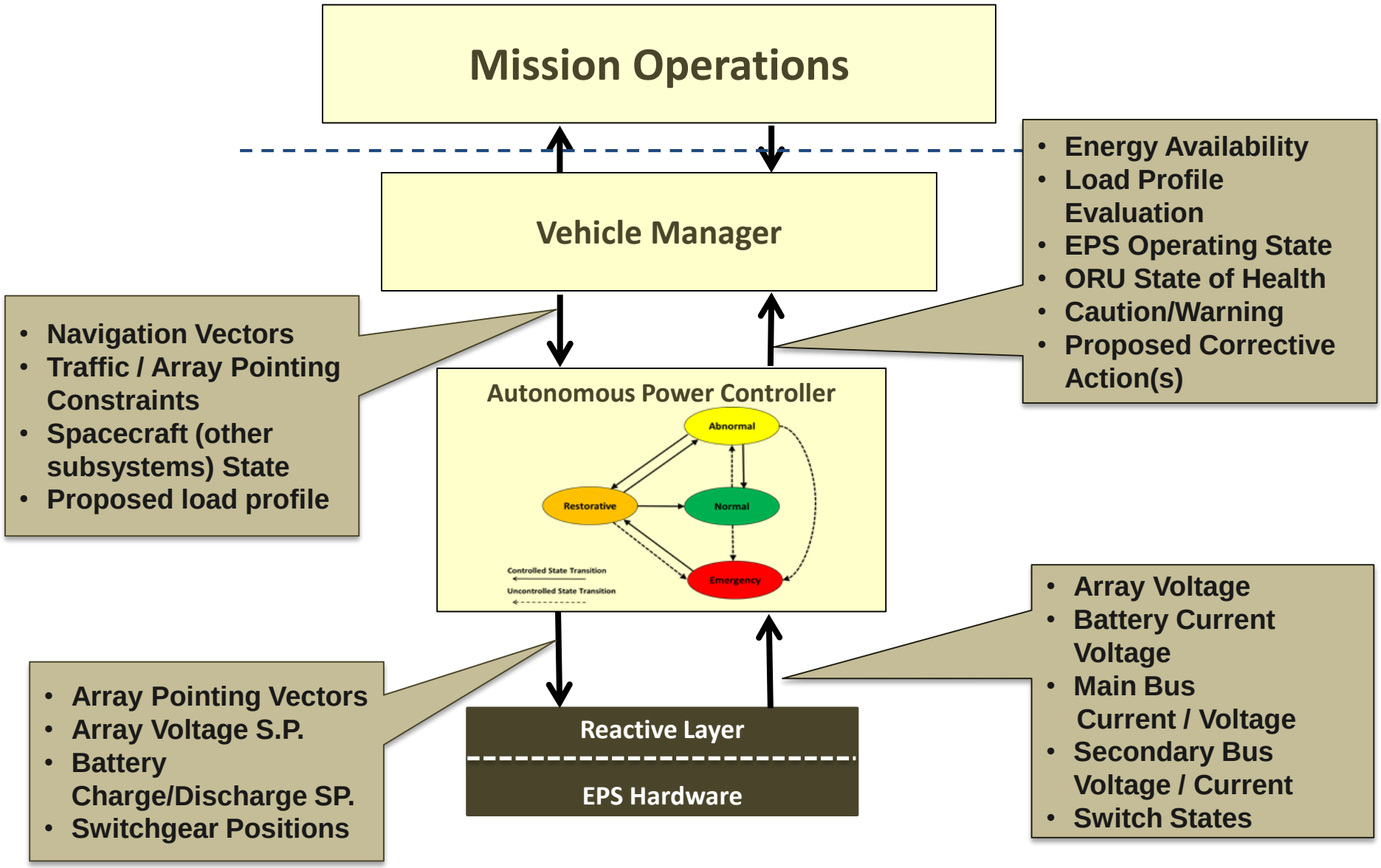
Vehicle Manager
- Plan vehicle operation to achieve mission objectives
- Coordinate vehicle subsystems

Autonomous Power Controller
- Monitor / control normal mode of operation
- Respond and report faults of the EPS system

EPS Hardware (Reactive Control)
- Provides close-loop control of the EPS hardware

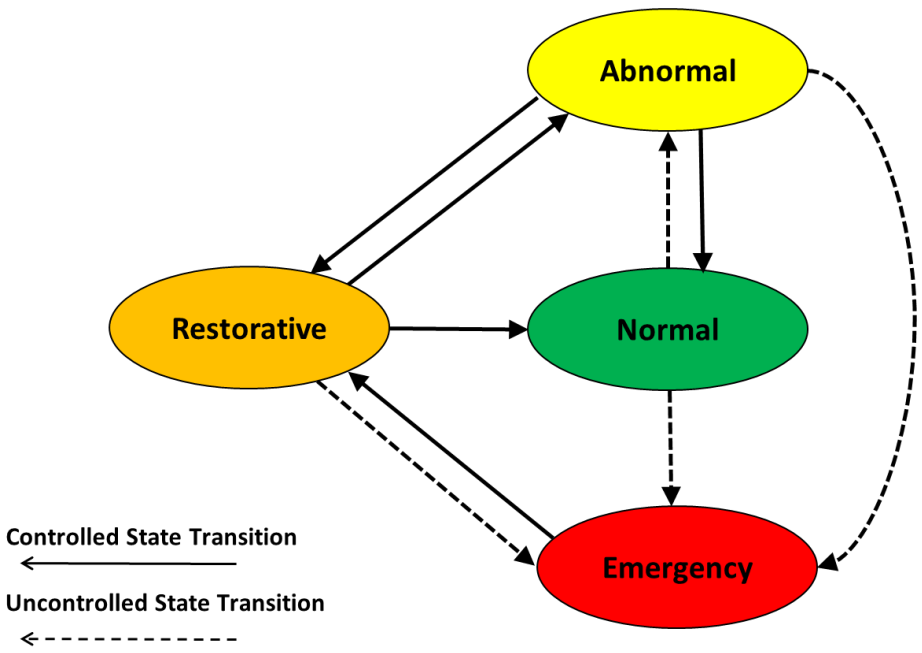


Intelligent Controller Data Flow



Autonomous Control State Diagram

Assess / Manage Power System State



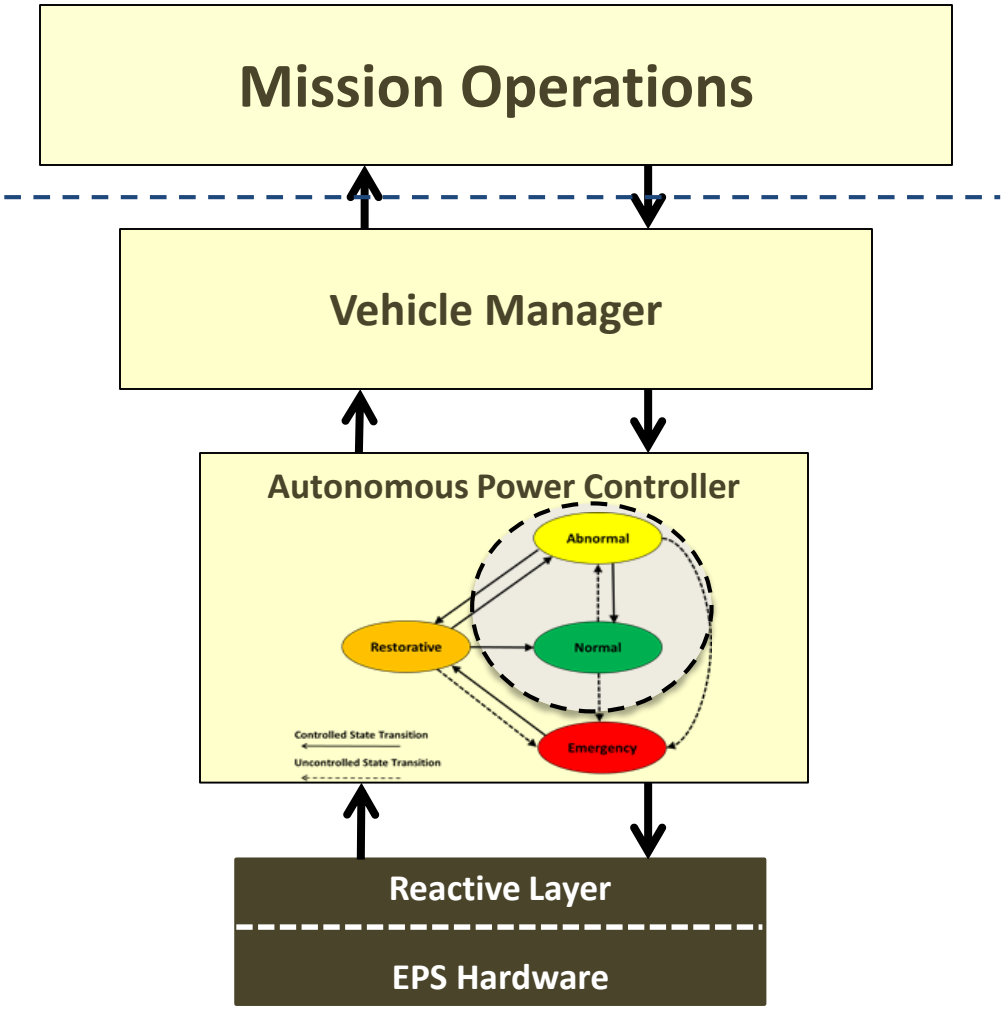
- **Normal State -- Normal operation, system operating on plan, continue indefinitely without interruption**
- **Abnormal State – No faults in hardware but system is not performing as planned**
- **Emergency State – Fault occurs – relieve system stress and prevent further deterioration**
- **Restorative State – System is degraded but safe – restore power flow to all loads in a safe manner in minimum time**

Autonomous Power Functions

Normal Mode Control Functions

Normal / Power Controller

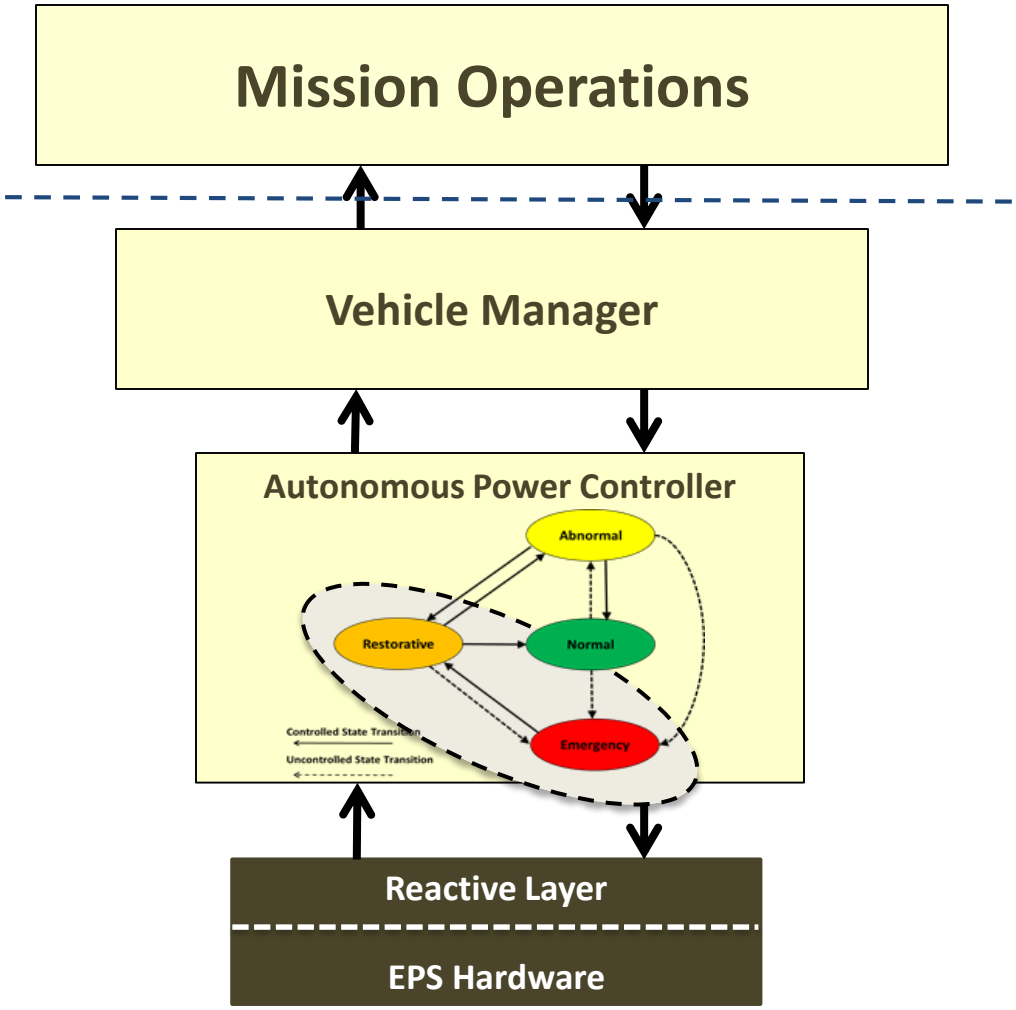
- **Provides the Vehicle Manager with power availability**
- **Coordinates with Vehicle Manager to develop a workable load schedule**
- **Executes Vehicle Manager load schedule**
- **Coordinate re-planning in Abnormal Mode when schedule is “broken”**
- **Optimizes energy utilization**
- **Optimizes distribution system utilization**
- **Maintain power quality within the distribution system**
- **Send configuration information to the reactive layer control**



Fault Mode Control Functions

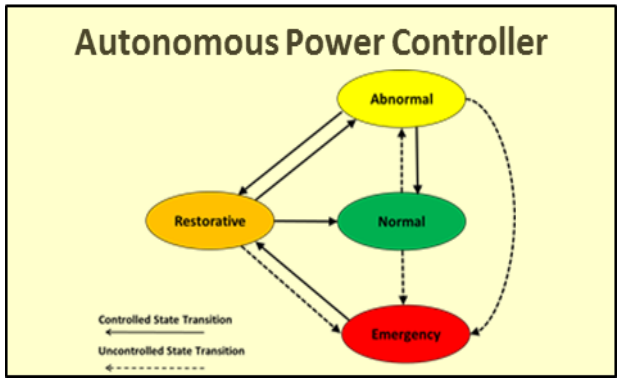
Emergency / Restoration States

- **"Safes the System"**
- **Reports "Emergency State to the Vehicle Manager C&W System**
- **Identifies the fault**
  - **Hard Faults**
  - **Soft Faults**
- **Develops a restoration plan to restore the system to Normal State**
- **Coordinates restoration plan with the vehicle manager**
- **Executes the restoration plan through the Reactive Layer Control**



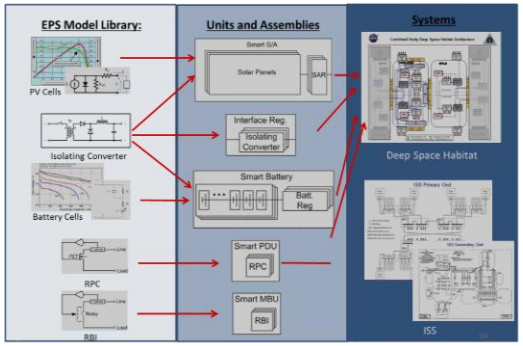
Autonomous Controller Evaluation and Test

Test and Evaluation Approach



Autonomous Controller

Deep Space Vehicle Power System Test Bed



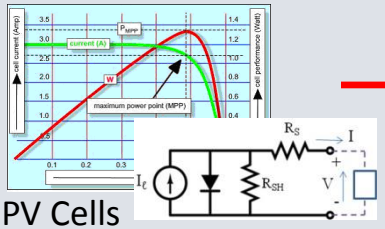
Real Time Simulation

Dynamic Electric Power System Modeling

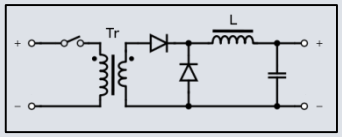
- **Currently leveraging the Air Force INVENT Program approach to develop common Electrical Power System (EPS) elements to be used within space electrical power system simulations.**
  - Library of elements can be used on any number of configurations and used to simulate various power system Simulink applications
- **Simulation characteristics include the following:**
  - Provides real time, dynamic simulation of multiple connected power systems such as multiple channels of ISS or Deep Space architectures
  - Average value modeling of power electronics
  - Faster, accurate circuit simulation for switching elements based on state equation approach
  - Features a communication infrastructure to synchronize simulations running on multiple processors.
- **Validation of the EPS elements was achieved by simulation of interconnecting channels of ISS and comparison to available ISS power system Saber hardware model data.**

Electrical Power System (EPS) Simulation Development

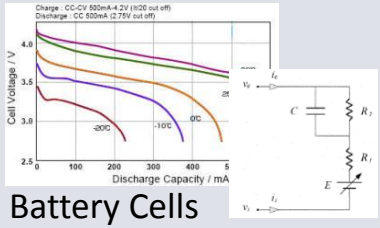
EPS Model Library:



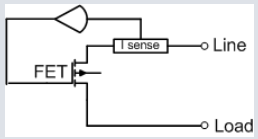
PV Cells



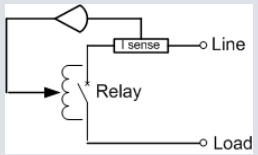
Isolating Converter



Battery Cells

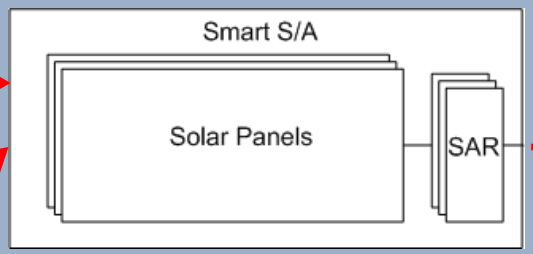


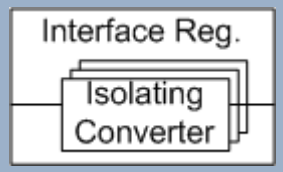
RPC

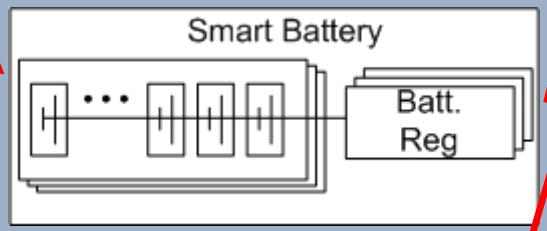


RBI

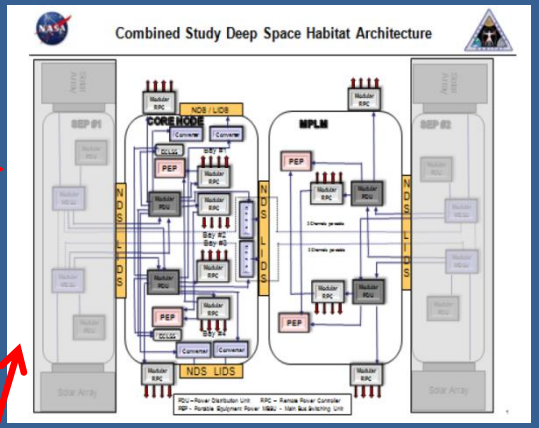
Units and Assemblies



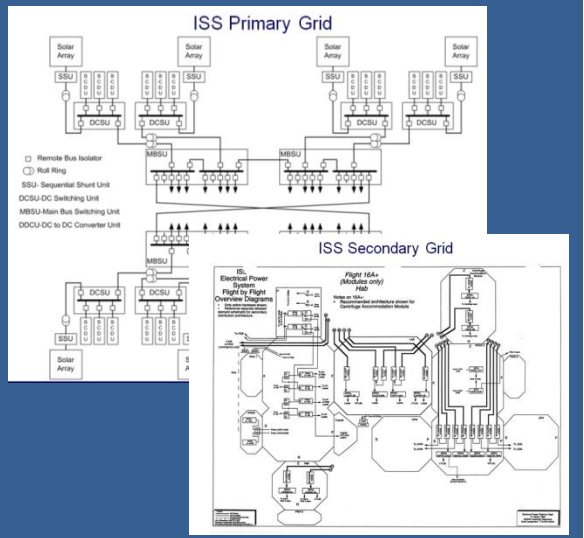




Systems



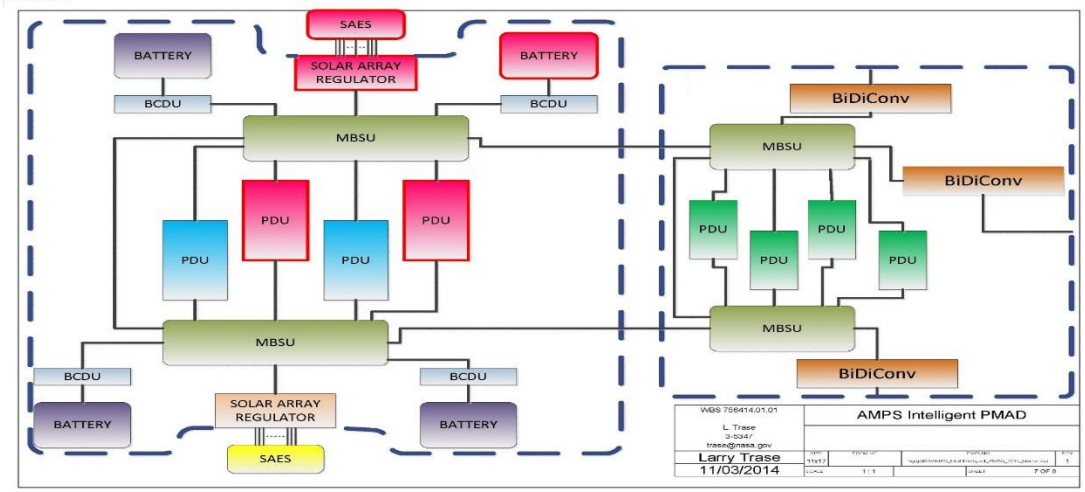
Deep Space Habitat



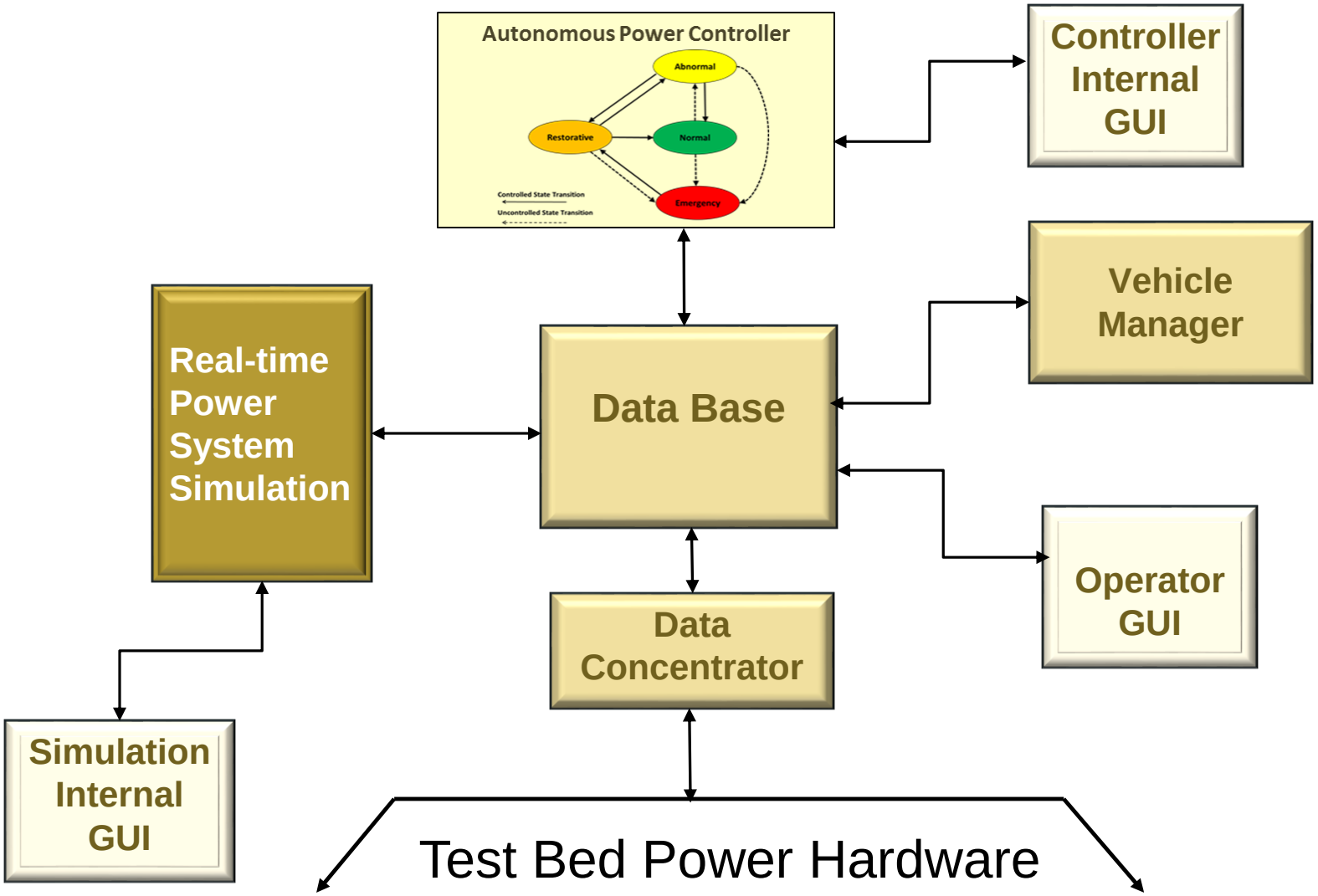
ISS

Autonomous Power System Test Bed

- Evolving into a platform to evaluate the performance of the autonomous control with real hardware
- Contains
  - Solar simulators / regulators
  - Batteries / simulators
  - Power Distribution Equipment
    - MBSU's
    - PDU's
  - Multiple Load Types



Autonomous Control T&V Configuration



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Status and Future Plans

Accomplishments:

- Defined initial autonomous vehicle control architecture
- Implemented distributed facility to develop and test the Autonomous Power Controller (APC), Vehicle Manager, and test bed hardware
- Developed a real-time simulation of the Deep Space Habitat power system
- Developed prototype of an Autonomous Power Controller (APC) for Normal Modes capable of long-term energy management
- Demonstrated APC controller with remote hardware at JSC
- Defined, implemented, demonstrated the interface between APC and Vehicle Manager

Future Plans

- Develop capability to identify power system faults
- Develop contingency options to accommodate faults
- Integrate GRC power system test bed for hardware in the loop evaluation

Summary

- **Intelligent Power Systems are key for long term missions and operations far from earth.**

- **Development of an Autonomously Controlled Spacecraft is consistent with the "Future of Human Space Exploration" roadmap and enables the transition from "Earth Reliant" systems to "Earth Independent Systems".**

- **Verification of developmental space EPS autonomous power controllers will be achieved through real-time EPS simulations, hardware in the loop and power system test bed validation efforts.**

References

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- Dever, Timothy P., May, Ryan D., et.al. Autonomous Spacecraft Communication Interface for Load Planning, NASA-TM 2014-218362, November 2014.

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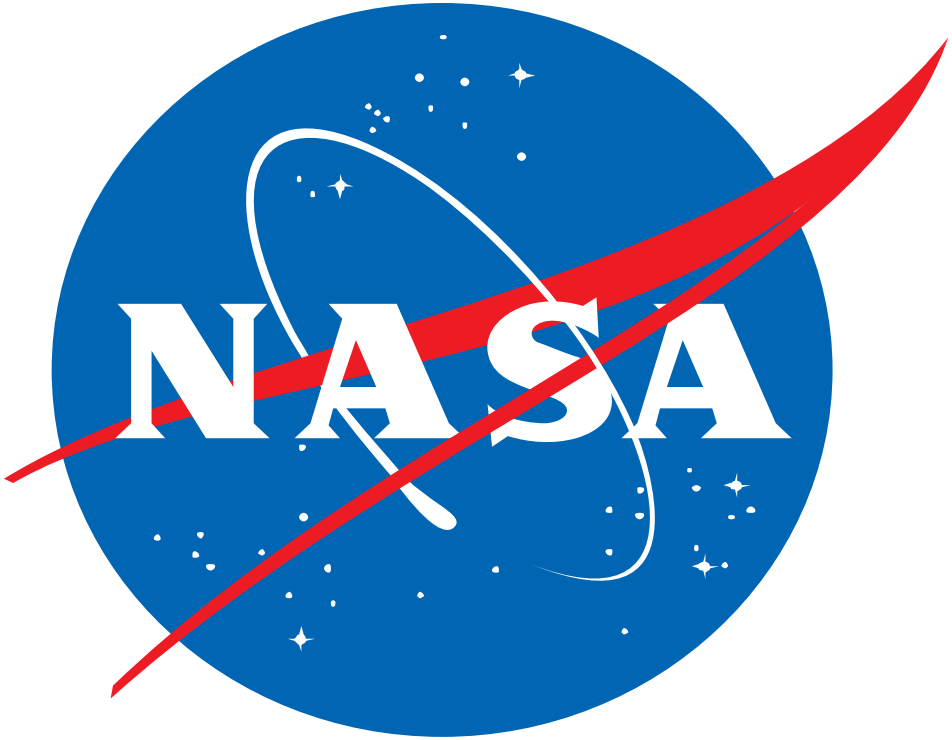

Questions???